

HYPERSONIC FLIGHT VEHICLES: PERSPECTIVE AND PROGNOSIS

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Abstract

Although hypersonics has been with us for over 50 years, the great advantages of very high-speed flight have not been brought to engineering fruition. The present paper gives a brief over-view of hypersonic flight, including the often neglected chemical reactions and upper atmospheric characteristics which **MUST** be included for realistic studies. The lack of ground test facilities with **COMPLETE** simulation of hypersonic flight is, in the author's view, a major impediment to ever developing, in some rational way, hypersonic vehicles with very high performance. There has been little facility research since the early 1970's and **NO** continuing effort to examine possible solutions because of the long lead time required to research and test such techniques. At the same time, current and future systems, which might take advantage of a very high-speed flight regime, are severely handicapped by long lead times (beyond the project plans), and the expense of funding the research and development needed. Long lead times and expensive test set-ups are required to evaluate **ANY** hypersonic facility proposal, but "flight test development" is even more costly and time consuming. Modern computational capability and new knowledge bases in several key areas have been developed (briefly reviewed in the report) **BUT**, detailed testing is needed to validate concepts and preliminary designs. If we can't build a ground test facility, I suggest we can't build a vehicle!

Introduction

After fifty years of hypersonic research and development, there is no operational or experimental hypersonic flight vehicle, or even one planned. Considering the major achievements in flight, from the Wright Brother's first flight, to commercial airliners, to jet propulsion, to transonic flight, supersonic flight, and ICBM development, these progressions seem to have been made in much shorter time steps.

From someone who has been involved in the entire gamut, a particular (but biased) view might be that the very high rate of progress initiated in the late 40's, and

peaking in the 50's and 60's, was essentially shut down in the 1970's. It was re-started in the 80's (with the aerospace plane project) but without the framework of the extended fundamental work and trained experts of the 50's and 60's. In the author's view, the confusion of the 1990's is a result of the gap in the 70's, and the lack of valid long range plans. Long term goals, supported over the time frames required, no longer seems possible. Hypersonics, which is a "new" field, continues to reside in paper studies and experimental concepts which, again in the author's view, are not supported by fundamental long term developments. Hypersonic flight is not an extension of what we think we know about supersonic flight. Projects and programs today are

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quite short term, while the development of the fundamental tools for hypersonic flight are long term. A review of the 50 years of hypersonic vehicle studies indicates fits and starts, gaps and peaks. We need a special definition of long term goals to really develop the potential, or even to examine the potential, of hypersonic vehicles.

This paper is the view of one who has been involved in the full spectrum of hypersonic vehicle research. The present study is not supported by any agency of the government, and is solely the views of the author. The paper will present this view in three groupings: 1) an overview of hypersonic flight, the fundamentals and the definitions, 2) a look at the question of why even consider hypersonic flight, and 3) what is really needed if there is going to be a future rational development of hypersonic vehicles. It includes some brief outlines of long range plans which were originally part of hypersonic vehicles development.

Overview

Flight regimes in the atmosphere

Figure 1 gives the classical altitude versus velocity plot with a few examples of applications. The top of the atmosphere (sort of the beginnings of space) is above about 300,000 ft. The velocities extend to about 40,000 ft. per second, which is approximately the speed of a returning planetary flight. Only the small region in the lower left hand corner, identified as "current" aircraft, and some exploratory studies at low speeds to quite high altitudes (~100,000ft), have been exploited as "flight" regimes. The top operational speed, for example, of the SR-71 was about Mach 3, and flights to 60-70,000 feet were routine. The top speed of a piloted vehicle, the X-15, reached a Mach number of 6.8 before it ran

out of rocket fuel. All other applications on Fig. 1 are transient. We have learned how to "endure" some high speed flight problems. What is clear from this plot is that there is a major area of velocity and altitude which we have not exploited as a possible "field of operation" for aerodynamic vehicles.

This plot (Fig. 1) gives little indication of the problems involved, and can be supplemented by Fig. 2. This figure (on the same altitude/velocity coordinates) presents a set of parameters which, approximately, describe some of the important engineering factors which are involved. The dashed (somewhat vertical) lines, labeled "Wind Tunnel Reservoir Temperature ($^{\circ}\text{R}$)" is the theoretical (approximate) stagnation temperature. It is the temperature which one would need, in a classical wind tunnel, to expand isentropically to the flight test conditions. The solid lines (sloping to the right), designated as "Wind Tunnel Reservoir Pressure (psia)", is the stagnation pressure that would be experienced by a vehicle in flight. It would be the requirement if one were going to simulate this flight condition by a classical wind tunnel, expanding isentropically from stagnation conditions. The approximately parallel solid lines, indicated as "Flight Dynamic Pressure (psia)", have been included as part of the general background for classical flight dynamics advocates (where such numbers are important in flight control).

This plot, even approximately, still does not define the fundamental parameters which differentiate low speed, transonic, supersonic, or hypersonic speeds, nor any of the variations with altitude. For this, one will have to look at several parameters in detail.

Detailed Altitude Effects

Although most piloted vehicles (in the past) have operated at altitudes below 60-70,000 ft., the possible flight envelope extends from sea level to approximately 300,000 ft. Although the atmosphere does not end abruptly, the density at this altitude has become so low that most consider this the start of the "space" regime. An examination of the details of the atmosphere, from sea level to this point (the regime of the atmospheric physicists) covers a very crucial series of parameters (for example, Ref. 1).

The pressure falls continuously as one goes from sea level to altitude. However, the density is not a monotonic curve because the temperature variation is not a smoothly varying function. Although the density generally decreases with altitude, there are variations. The constituents (chemical) definitely changes with the altitude. Although we are used to working with an "almost perfect" gas called air (consisting of oxygen and nitrogen molecules, and a multitude of trace elements), there are very important variations which may have a decisive effect on various elements of hypersonic vehicle design. For example, water vapor (an important factor in chemistry) is almost non-existent at the higher altitudes. The molecular constituents, at lower altitudes, are joined by atoms, ions, and active particles at higher altitudes. There is a very important ozone layer of active oxygen, which is important to the earth's environment. There are many trace elements (again, perhaps important in certain chemical and physical reactions) which vary considerably as the altitude varies, for example, see Fig. 3, from Ref. 2.

As the pressure decreases (altitude increases), the treatment of the atmosphere as a continuum has to be modified as the time and distance between particle interactions becomes large. At very high altitudes, one approaches what used to be called the "free molecular region". This region was originally considered as simple interactions between "billiard ball-like molecules," with interactions "every once in a while." There is now the realization that this region is inhabited by many active particles, and the interactions are not "billiard ball-like" but must include a whole range of possible chemical reactions as particles interact. To make the atmosphere even more complex, there are clearly temporal and spatial variations, which depend on sun activity (sun spots), location (global), time of year and time of day. In general, the characteristics of the upper atmosphere varies widely in many ways. These results have become much more available over the past couple of decades, with the upper atmospheric physics studies that have been made, both from the ground and from satellites. An example of some of these publications are Refs. 1-3, and the extensive studies in the Series of Publications, such as Ref. 4. The altitude effects (not shown in Fig. 1) might be shown simply as a "slowly increasing effect" as altitude increases, Fig. 4.

As Speed Increases

Although Fig. 1 used, as a horizontal scale, velocity (in feet per second), it suggested the possibility of using this scale as Mach number if the speed of sound was defined as that at "standard atmosphere." It is clear from the previous discussion that the local speed of sound is not constant with altitude, and so the horizontal scale, sometimes referred to as Mach number, is not valid.

As the speed increases, the stagnation temperature (for example, at the nose of a vehicle) increases approximately as $1 + 0.2 M^2$. This is a simple approximation. Along with the stagnation temperature variation with velocity, the recovery temperature (the temperature on a wall under a laminar or turbulent boundary layer) also increases ($\sim 0.9 T_0$). Since there is a considerable difference in recovery temperature beneath laminar and turbulent layers, detailed information on where transition occurs on a vehicle becomes more important as the speed increases.

The initial problems associated with increasing stagnation temperature and recovery temperature are primarily material problems. If one goes back to the old designs of airplanes made of linen and bamboo, to the changes to aluminum (which has been the primary building material for many years), the problems of increasing speed are clearly associated with the construction materials. For example, the SR-71, which flew at Mach numbers of about 3, experienced recovery temperatures beyond that permitted by aluminum. Titanium permitted the construction of a vehicle which could fly at 3, but higher speeds would probably require materials with higher operating temperatures. If radiation cooling is going to be the main parameter, new higher temperature materials will be needed. Active cooling brings a whole new view to the problems associated with materials in high-speed flight.

This all results in the concept of something called a "thermal thicket." It depends on the vehicle materials being used. The entire vehicle construction – skin, internal structure, cooling, etc. – depends on the engineering approach to solving the heat transfer problems as speed increases, with little effect of the atmosphere details or

supersonic theory or practice. This is indicated in Fig. 5, where the effects of the "thermal thicket" has no initial value, but simply becomes more difficult as the speed increases. During the initial part of this thermal thicket, the usual aerodynamic parameters of Mach number and Reynolds number remain paramount, with an "almost" perfect gas approximation being realistic. At somewhat higher temperatures (depending on configuration and details) a variation of the specific heat ratio C_p starts to become important.

The previous discussion has not included any of the problems associated with going from subsonic to supersonic flight. This is a well known and discussed historical observation from incompressible low speed flight to transonic and supersonic flight, where flow compressibility and Mach number are both important. There is, however, the question of where hypersonic flight starts. It is usually "grossly" defined as Mach numbers considerably greater than 1, ($M \gg 1$).

Figure 6 is an approximate sketch of the low supersonic flow around a simple body (axisymmetric or two-dimensional) with the relatively weak shock wave and an approximation of waves on the top of the body, and the boundary layer and streamlines on the other. At low supersonic speed, the shock stands off from the body at some distance. The stagnation streamline (noted on the figure) can be calculated, in detail, from the free stream, across the shock, and then coming to a stop at the stagnation point on the body. A good approximation of this can be done using the perfect gas approximation. The waves generated by the body (after the sonic line) reflect from the bow shock. These waves are all weak and the approximation of zero pressure gradient normal to the body

downstream of the nose is reasonable. If one looks at streamline (a) and (b), and the boundary layer development along the body, all of this can be reasonably well approximated. The flow field normal to the body is approximately of constant stagnation pressures, stagnation temperature, and with "almost perfect" gas characteristics.

At Mach number considerably greater than 1 ($M \gg 1$), the picture changes dramatically (Fig. 7). The shock standoff distance at the stagnation point is much less. To calculate the flow characteristic along the stagnation streamline, the shock wave is so strong that the pressures and temperatures after the shock wave require the inclusion of chemical effects. The deceleration of the flow from the shock wave to the stagnation point takes place with considerable chemistry involved.

The strong wave system, generated by the body after the sonic line, reflects from the strong bow shock, and the approximation of a constant pressure normal to the body is not valid. If one looks at streamlines (a) and (b) in detail, the differences between streamline are important. Each streamline goes through a different strength shock wave, with significant differences in stagnation pressure losses, stagnation temperature and chemistry. The chemistry varies along each streamline, so that each streamline has a unique set of chemical characteristics and changes with distance (time). The flow swallowed by the developing boundary layer is different at each downstream station. It is clear that the flow, with Mach number much greater than 1 ($M \gg 1$), results in a considerably different flow field around the body than the one generated at a low supersonic speed. In a real vehicle, approximated in Fig. 8, an example of the streamline differences would be streamline

(a) over the top of the body, and streamline (b) going under the body, into an inlet. Streamline (a) would go some distance before it interacted with the tail surface. Its characteristics at the time of the interaction with the tail and the control surfaces, will be very much different (because of the chemistry and wave system) as compared to the flow entering a possible air breathing engine under the body (Streamline b). The exit jet flow (c) is a different gas (burned fuel and air). The gross effects of temperature on air (flow field) is shown in Fig. 9, which indicates that chemical effects start at $M \sim 5/6$. The chemical effects on the flight regime is shown in Fig. 10.

Hypersonics, by these definitions, is a "new" field. It not only encompasses Reynolds number effects of low speed flight (the viscous-inviscid interactions), the Mach number effects of compressibility (transonic, supersonic, wave drag and wave angles), but includes a new parameter Damkohler number, D_a , which characterizes the chemistry varying along each streamline. The reaction times versus particle times of flight (D_a) in the test media are crucial in defining these effects. If one tries to include all three of these parameters (Re , M , D_a), one finds that there is no scaling law that we know of (at present) which can be used. Our reliance on Reynolds number and Mach number scaling at supersonic speeds is invalidated by the need to duplicate the Damkohler number. Since the chemical processes are complex, the D_a depends not only on the body geometry but also on the characteristics of the medium through which one is flying. There is, at the moment, no way to scale truly hypersonic flow.

This "new" field of hypersonics is quite different than most of the conventional thinking at lower speeds. For example, the wave drag of an optimum body at

supersonic speeds begins to exceed the skin friction drag at Mach numbers of the order of 4 or 5. This means that the configurations, usually considered close to optimum at low supersonic speeds, may not be anything like the configuration to optimize lift to drag ratio or minimum drag at very high speeds. Another consideration, for example, is the use of velocity or Mach number as a parameter. It should be noted that the definition of hypersonics is usually $M \gg 1$. One might consider the energy involved in the flight vehicle. The energy is approximately proportional to the square of the velocity. A vehicle at a Mach number of ~ 10 (10,000 ft/sec.), has only about 14% of the energy required to orbit. The velocity (or approximate Mach number) of flight has to exceed something like 18,000 ft/sec ($\sim M-18$), to be at half the energy level required to orbit (roughly Mach number of 26-27).

Why Hypersonic Vehicles?

For almost four decades, there has been extensive discussions about the "why" for hypersonic flight. The primary rationale has been TIME. At very high speed flight, any point on the globe can be reached in a fraction of an hour. In addition, the flight path is radically different than the usual aerodynamic vehicles. At very high speed, the lift is not required to compensate for the weight of the vehicle since a significant part of the weight is compensated by centrifugal force. As noted earlier, as the Mach number goes up, the drag is effected more and more by wave drag. To repeat an earlier observation, above Mach numbers of 4 or 5 most bodies have more wave drag than skin friction drag. The configuration studies of hypersonic bodies seem to have little relevance to this fundamental phenomena.

There is, in the author's experience, few hypersonic applications which haven't

been studied, in some detail, by either the Air Force or NASA. The planning offices of the Air Force have always (over the past 40 years) included a major section on hypersonic applications which are perhaps worth reviewing in the light of some of the current proposals.

The "classical" discussion about hypersonics seems to be tied to either entry to space (ground to orbit), re-entry, or some cruise missile. There are some applications where the hypersonic flight vehicle never flies other than at hypersonic speeds. An example may be the "trans-atmospheric vehicle," discussed in detail decades ago. It is a possible technique for orbit shift (which can not be done with fuel and present rocket technology). This hypothetical vehicle would descend from orbit into the "free molecular" or "slip flow" region (perhaps dipping into the continuum atmosphere), all at very high speeds. It would change orbit parameters, and re-enter space in a "new" orbit. Optimum lift to drag ratio is crucial to such an application but, at least in the author's experience, this possible application was never investigated because we had neither the theoretical or experimental possibility of examining the problems in detail.

Another example might be demonstrated by examining some of the SR-71 operations at Mach 3, where very high altitude flight had no sonic boom corridor on the ground. Also, at sufficiently high altitudes, there is no polluting of the atmosphere.

Possible Solutions, Prognosis

Solutions to hypersonic vehicle problems require a "back-to-basics" approach [Ref. 5]. The study of the combination of parameters, Reynolds

number, Mach number, and Damkohler number, has not been undertaken in a major way. Many of the recent books on hypersonics are really concerned with hypersonic aerodynamics of "almost perfect" gas, where Reynolds number and Mach number are the key parameters. Most of this material is covered in the early work of Hayes and Probstein [Ref. 6]. The key problems of hypersonic scaling, which is so classical to lower speed flight, does not seem to apply in the hypersonic regime. This means that test equipment must be large, and the energy levels must be very high.

The tools required for the examination of hypersonic problems are well known and can be briefly summarized as 1) instrumentation, 2) computation, 3) chemical kinetics, 4) boundary conditions (including wall cooling by many techniques) and 5) an understanding of gas constituents so that the work on chemical kinetics is applicable at flight conditions. The combination of parameters Re , M , and D_a , as well as the varying conditions in the atmosphere, make the full solution for the entire hypersonic flight problem a daunting one. A key requirement for research in this area is to construct validated models which cover the primary problems under consideration. An examination of all of these parameters might be briefly summarized in a "good news - bad news" framework. The "good news" is that, in the last decade or two, new tools have been developed which were not applied in much of the work of the past. Instrumentation and computation are extraordinarily more capable today than they were 20 years ago. Point instrumentation (optical, non-intrusive) is now capable of making all of the specific measurements required. These measurements could provide a unique new insight into hypersonic flow fields. Computational aerodynamics can solve

almost all aerodynamic problems. The increased inclusion of chemical kinetics with the aerodynamic computations hold promise of providing full solutions. The "bad news" is that we have no way to test the modeling or the details supplied by the new instrumentation and computation. There are NO ground test facilities at Mach 10 or higher, which fully simulate flight [Refs. 7-10]. The range, from sea level to 300,000 feet may, in many applications, be defined in a much narrower band. But, a general study of the area covers an enormous area of different physical phenomena. In addition, test facilities with very short test times limit the study of chemistry and engineering parameters by not providing full simulation of the actual flight conditions over sufficiently long time periods.

The need for test facilities which fully simulate (for some significant time) the hypersonic flight problems are a key element in providing fundamentals, as well as validating computation and modeling. This requires a long term commitment to examine and build, as well as a commitment to long term programs to be carried out in the facilities.

Discussions of the tools for hypersonic research always results in flight versus wind tunnel testing arguments. There is no question that we will always need flight validation "BEFORE" a full commitment is made to the construction of hypersonic flight vehicles. HOWEVER, flight research is very expensive and time consuming. Testing ALL systems in flight, when you have no idea of how to check them out beforehand, is a daunting problem. We must have ground test facilities which can test "iron birds." One has to make sure we have solved the problems that we know about. The final flight test is to determine

whether there are problems that we didn't know about. The idea of building a flight vehicle, without the capability to test most of the problems that we know about on the ground, seems unreasonable.

The author suggests that we have done little in the way of wind tunnel research, specifically for hypersonic activities, since the early 1970's. This area of research and development has usually been denigrated by the following types of comments:

- 1) It will take too long a time to develop, and there is no project or program that requires this type of capability.
- 2) It will be too expensive, and we have no project or program that can afford it. Hypersonic flight simulation is very energy intensive.
- 3) Let's try to build something small and see if it works. Then scale it up.

The author suggests that all of these statements are inconsistent with a rationale approach to the evaluation of hypersonic vehicles. If you don't know and can't demonstrate what the possible capability of hypersonic vehicles are, it is difficult to say that anything will take too long to develop if future capability is really important. Ground facilities of unique capability are always expensive (compared to something) and current projects or programs seem to be a poor way of trying to support examinations of the future. An understanding of the energetics of hypersonic flight, for example, as compared to proposing a single stage to orbit, might put the energy view in some reasonable perspective. The usual concept of building something small, and applying this to the development of hypersonics research tools, seems to show a lack of

understanding of the importance of Damkohler number and the chemistry involved in hypersonic flight. IF it is important to understand and evaluate the potential benefits of hypersonic flight, one **MUST** consider the cost of examining the reality of this region before one does a cost benefit analysis.

One example of this "chicken and the egg" process can be demonstrated by a concept proposal in 1992 by Lempert, Miles, and Brown [Ref. 11]. This concept of a new type of wind tunnel design was driven by the many studies of the 70's and 80's regarding hypersonic facilities. **ALL** of the conventional approaches were stymied by the combination of the required very high temperature and very high pressures required in the stagnation chamber. As observed from Fig. 2, it is not possible, with any current technology, to build a conventional wind tunnel at Mach numbers in excess of 6 or 7. More importantly, the recognition of chemical effects showed that, even at these conditions, the constituents in the test section did not duplicate flight conditions. The new concept recognized that one might be able to get very, very high stagnation pressures if the gas were reasonably cool. This results directly in the conclusion that a significant amount of the energy to drive the wind tunnel must be added downstream of the throat section. This conclusion was reached in facilities research carried out in the 60's but, at that time, there was no technology which provided a possible solution. Magneto hydrodynamics was the only concept, at that time, which seemed to provide a possibility of accelerating a gas to high speed, but it had to be a conducting gas. The concept of Ref. 11 was to use ultra high stagnation pressures at reasonably low temperatures and add energy downstream of the throat by a radiation process which might include

electron beams, microwaves, and lasers (developed in subsequent studies). Since the whole concept relied on gas characteristics not heretofore explored, new technologies of radiation heating, wall cooling problems, and other supporting technologies, the original research plan (1994) was framed as an R&D program to provide results for an engineering study of such a possible facility. Within two years, the original plan was discarded, and the program has continued as a research program, doing much in the way of fundamental studies which might apply to a wind tunnel. The research under actual conditions for a useful wind tunnel have not been carried out because of a lack of funding and "long term" views. If such a program were carried out, it might indicate a new set of possibilities for a ground test facility which could reach well into the hypersonic regime, (as defined earlier in this report, Mach numbers of the order of 18, or half the energy to reach orbit). Many of the comments noted earlier were applied to prevent the development of the information base to evaluate such a facility.

Conclusions

1) The Air Force appears to have decided on a major "space-based" capability in the future. If this is to be realized, the requirements for ground to orbit operations, orbit to ground operations, and orbital shift capability become major elements of concern.

2) A long term view of space-based operation needs ground test capabilities not currently available.

3) Support for long term R&D facilities and concepts for truly hypersonic operation are crucial in carrying out 1 and 2 above.

4) A key element of a long term R&D program in hypersonics must be tied to ground test facility capabilities. Such facilities are needed, not only for fundamental work, but also for the exploration of many applications.

5) Possibilities for solutions to the hypersonic vehicle problems are not dead-ended, but require critical long term commitments and crucial reviews. A well documented proven data base is absolutely required before one can carry out cost benefit analyses and really understand the potential of hypersonic flight.

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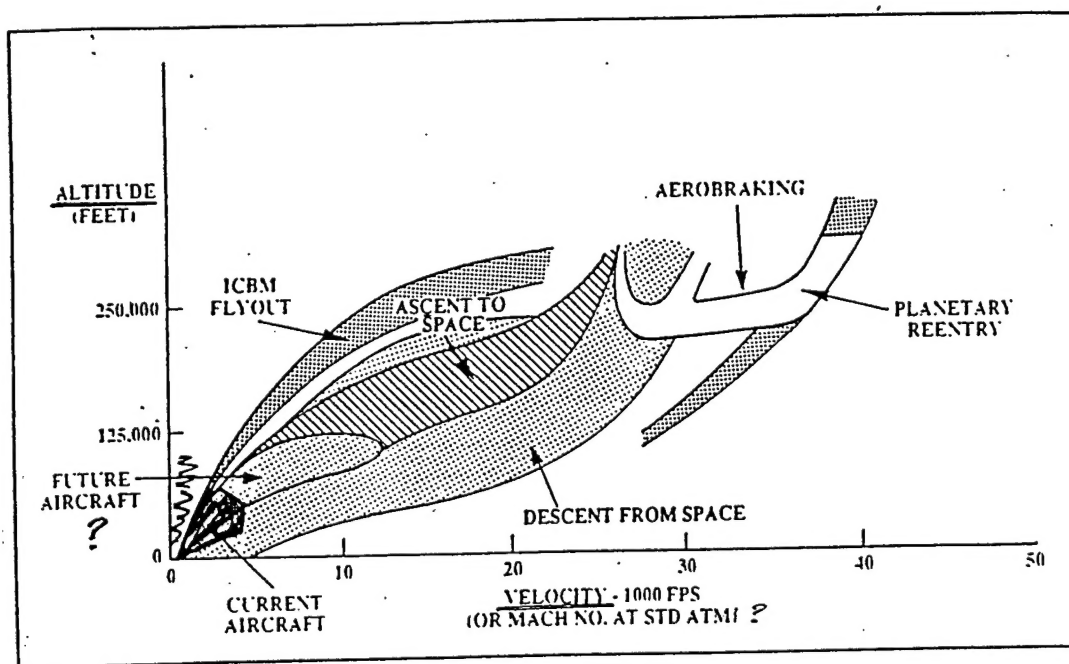


Fig. 1. The atmospheric flight regime and a few examples.

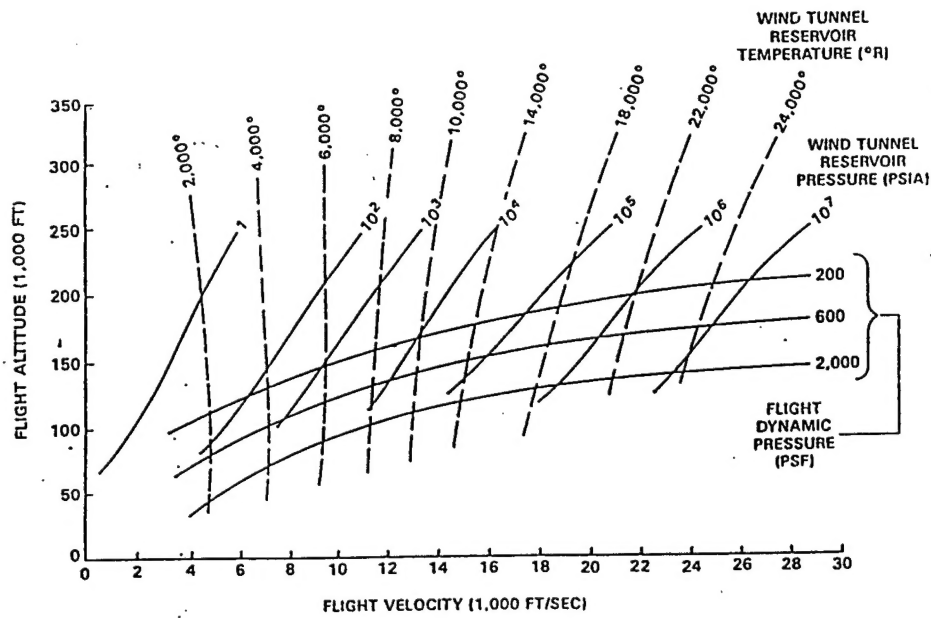


Fig. 2. The atmospheric flight regime, with some approximate physical parameters.

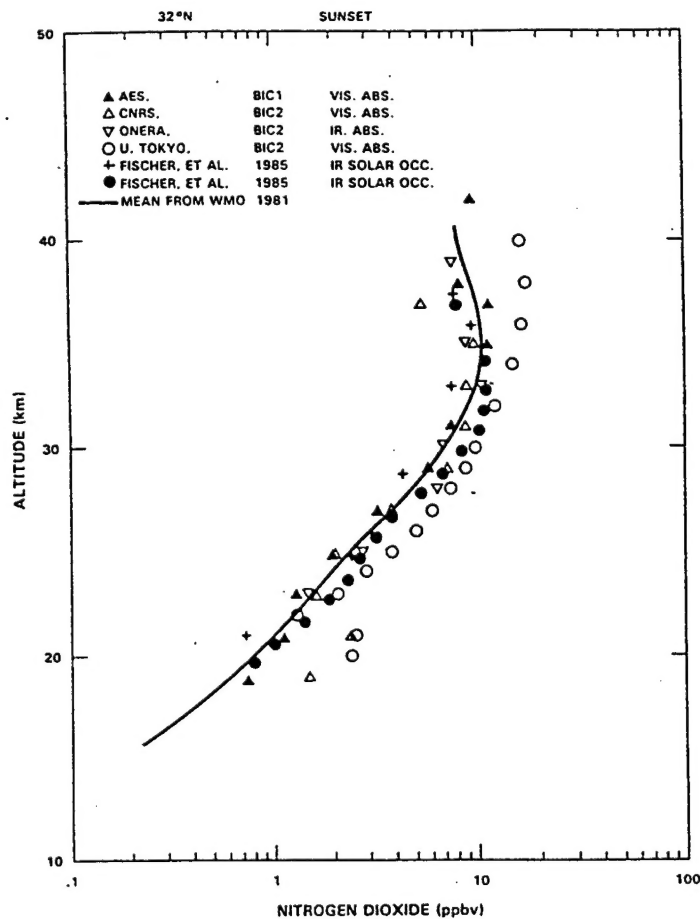


Fig. 3. Example of NO₂ variation with altitude (from Ref. 2)

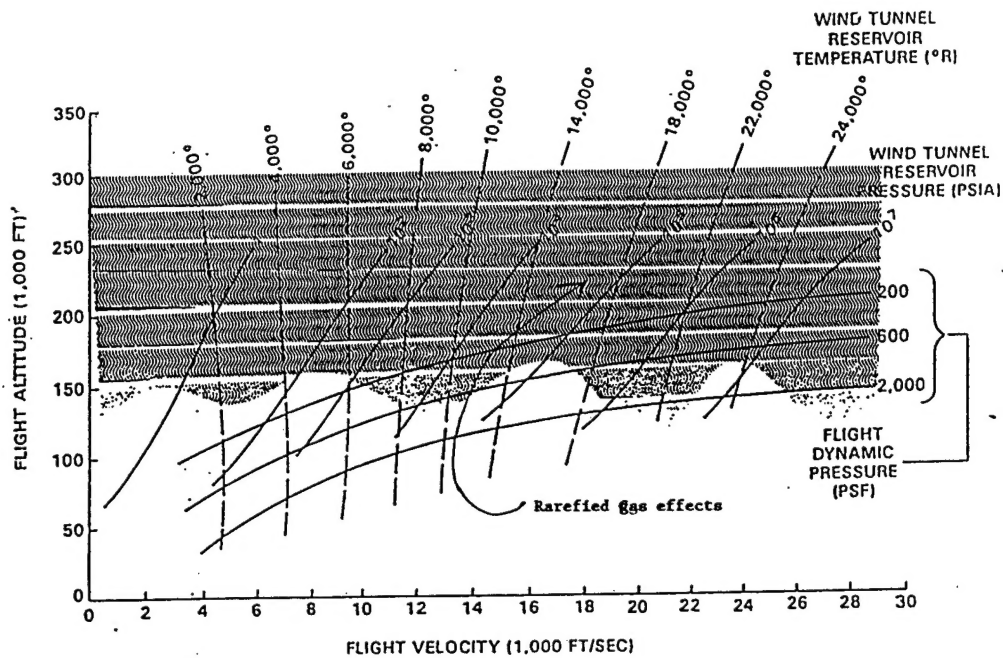


Fig. 4. Flight regimes of Fig. 2, with approximate region of high altitude effects.

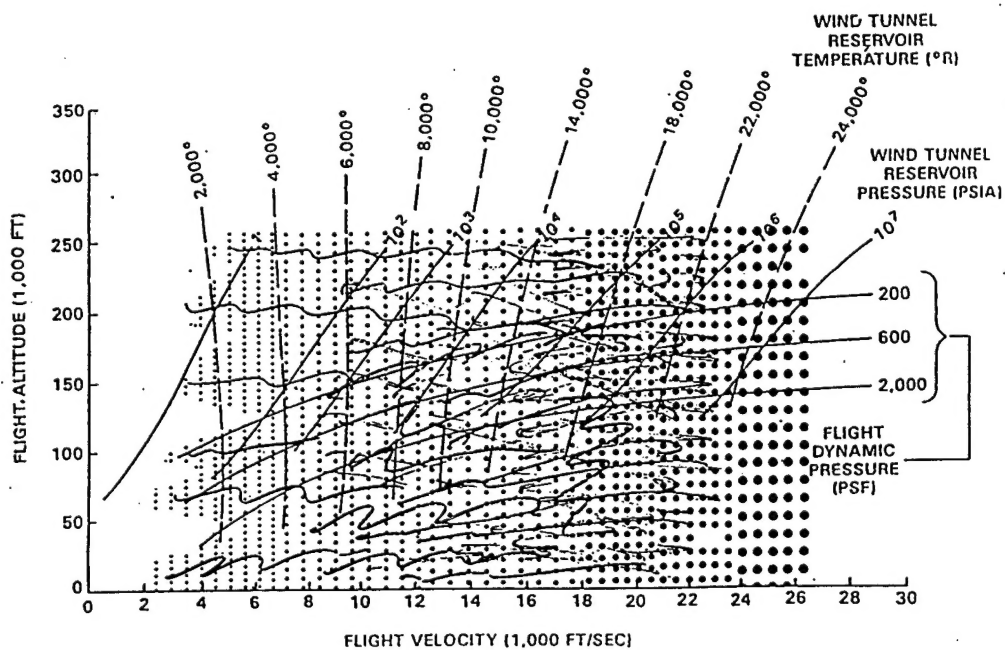


Fig. 5. Flight regimes of Fig. 2, with "Thermal Thicket" region (starting at $\sim M = 2$, useful limit for aluminum).

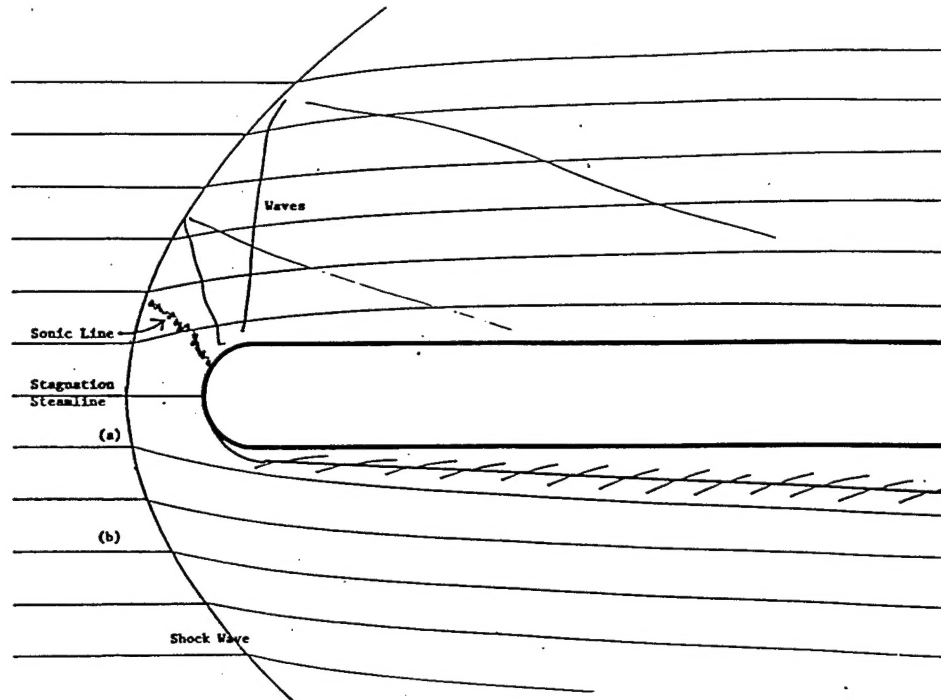


Fig. 6. Sketch of the flow field around a body, $M > 1$.

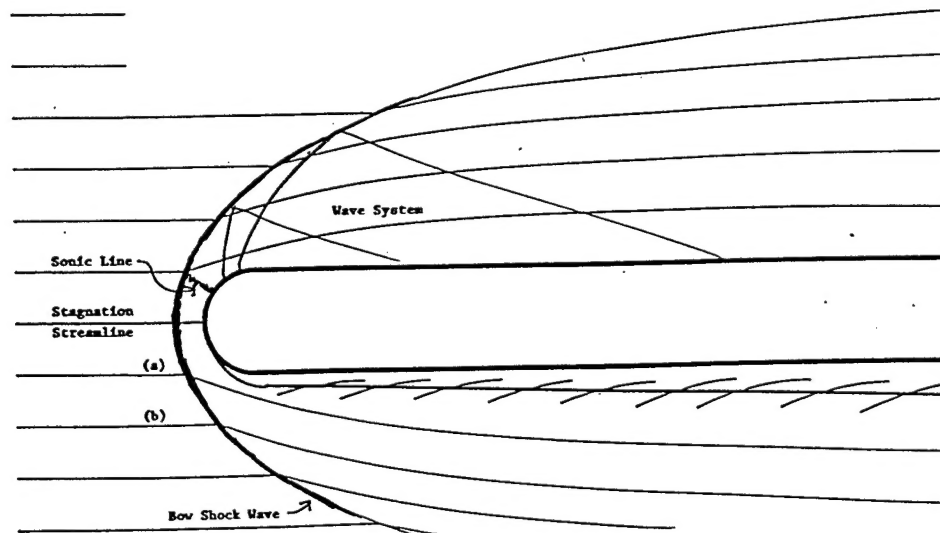


Fig. 7. Sketch of the flow field around a body, $M \gg 1$.

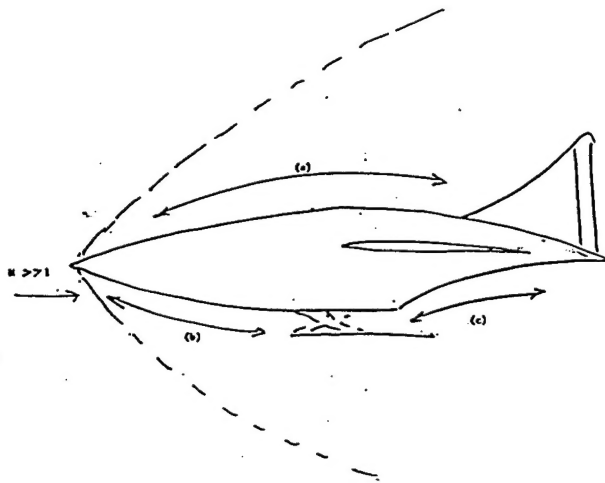


Fig. 8. Examples of flow paths around a hypersonic vehicle.

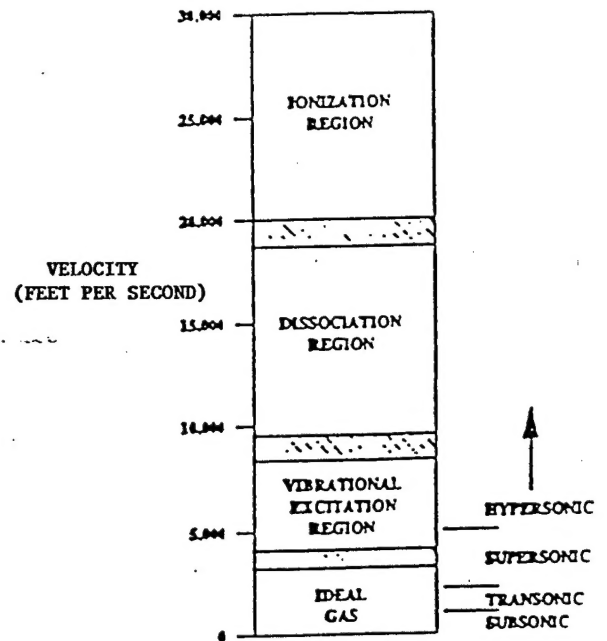


Fig. 9. Stagnation gas state for various flight velocities.

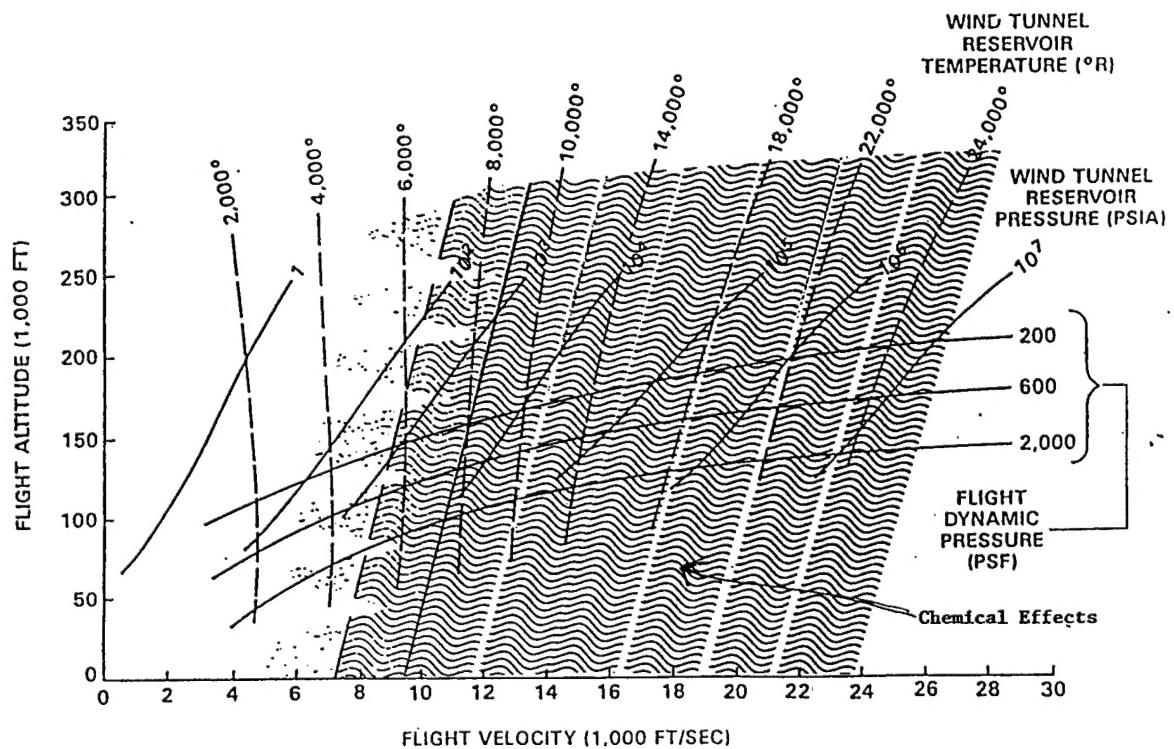


Fig. 10. Flight regimes of Fig. 2, with approximate chemical reaction region.